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Glacial Stratigraphy of northeastern North Dakota

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GLACIAL STRATIGRAPHY OF NORTHEASTERN NORTH DAKOTA

by

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This dissertation submitted by Howard Hobbs in partial fulfillment of the requirements for the Degree of Doctor of Philosophy from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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Lastly, I would like to express appreciation to my wife, Ann, whose untiring efforts especially during the last months, made it possible for me to finish this work.

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ABSTRACT

Seven lithostratigraphic units (formations) composed dominantly of glacial sediment have been recognized in northeastern North Dakota. Three formations, the Falconer Formation (Harris and others, 1974), the Dahlen, and Gardar Formations (Salomon, 1975) have been previously recognized. Four formations, the Hansboro, Vang, Tiber and Cando Formations are newly recognized. Uncorrelated units of glacial sediment are described but not named. The formations are differentiated and correlated primarily by the proportion of crystalline (igneous and metamorphic rock fragments), carbonate, and shale grains in the coarse-sand fraction (1 to 2 mm) of the glacial sediment. The proportion of shale grains was found to be the most useful criterion. Although all the formations are variable over the area of study, their shale content can be generally characterized as follows: Cando Formation, moderate to abundant; Tiber Formation, moderate; Vang Formation, sparse; Gardar Formation, abundant to very abundant; Dahlen Formation, moderate to abundant, Hansboro Formation, sparse to very sparse; and Falconer Formation, sparse to very sparse. These terms are defined as follows: very abundant, 80%-100%; abundant, 60%-80%; moderate, 40%-60%; sparse, 20%-40%; very sparse, 0%-20%. All the formations except the Tiber Formation generally contain more crystalline than carbonate grains. The distribution of the formations in the area of study can be summarized as follows: Cando Formation,

widespread in the west, patchy in the east; Tiber Formation, absent in the west, patchy in the east; Vang Formation, patchy over the entire area; Gardar Formation, fairly widespread over the entire area; Dahlen Formation, widespread over the entire area; Hansboro Formation widespread in the west, absent in the east, and Falconer Formation, absent in the west, widespread in the Red River Valley.

CHAPTER I

INTRODUCTION

Area of Study

The area of study is the northeastern corner of North Dakota. It is covered by the Devils Lake Quadrangle (1:250,000) and the part of the Thief River Falls Quadrangle west of the Red River (Figure 1). Most of the information presented, however, is on the eastern half of the Devils Lake Quadrangle and the western fourth of the Thief River Falls Quadrangle.

The study area is divided into two major geographic zones: the Drift Prairie to the west and the Red River Valley to the east, separated by the northwest-trending Pembina Escarpment. The bedrock under the Drift Prairie in this area is shale, primarily of the Pierre Formation. The Pembina Escarpment slopes to the east, with a drop in elevation of from 400 to 500 feet in a distance of 2 to 7 miles. The bedrock under the Red River Valley is primarily limestone and dolomite (carbonate), with some sandstone, silstone, and shale, particularly along the western side. The topography of the Drift Prairie and the Red River Valley is generally flat to rolling--the only rugged topography occurs along the Pembina Escarpment and the incised streams which cross it.

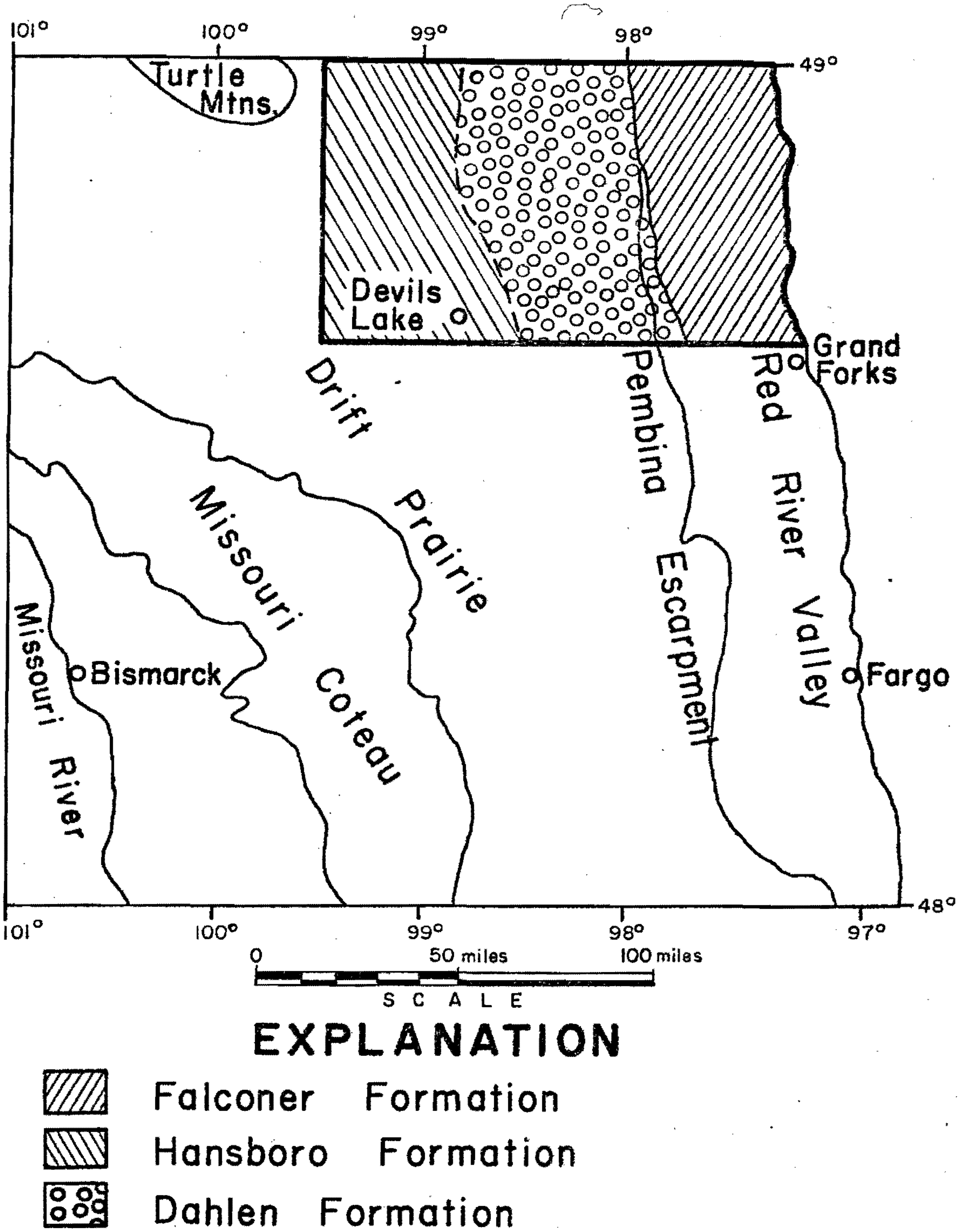

Fig. 1. Location of Area of Study, Showing Surface Lithostratigraphic Units.

Purpose of Study

The purpose of this study was to develop a stratigraphic framework to serve as a basis for understanding the Pleistocene history of the region and to serve as a basis for groundwater studies. Most of the good quality groundwater in North Dakota is obtained from Pleistocene sediments, particularly from sand and gravel deposited by meltwater streams. These sand and gravel bodies can be most easily correlated by placing them in a sequence of glacial sediments (tills), which, because of their consistent lithologic character, can be correlated over tens of thousands of square miles.

Previous Work in Area

Most of the counties in the area have been mapped geologically: Nelson and Walsh counties by Bluemle (1973), Pembina and Cavalier counties by Arndt (1975), and Grand Forks County by Hansen and Kume (1970). In these works no attempt was made to distinguish formations in the glacial sediments, except in the appendix of the report on Cavalier and Pembina counties, where Salomon (1975) defined the Dahlen and Gardar Formations and recognized several previously defined units, including the Falconer Formation. She also noted several units lower in the section, calling them Units 1, A, B, C and D.

Methods

Sample Collection

I collected surface samples during the summers of 1973 and 1974, mostly from exposures along roads and streams. The exposures are most numerous along the Pembina Escarpment and the streams incised through it. Core samples were obtained from Air Force engineering test borings; cuttings samples were obtained from North Dakota State Water Commission testholes.

Sample Processing

All samples selected were described; the lithology (till, silt, sand, etc.), color, and general lithology of the pebbles and coarse sand were noted. The samples were analyzed for texture, using the Standard North Dakota Geological Survey sieve and pipette method (Moran, in preparation) at first. During the study, the method was changed to the sieve and hydrometer method (Moran, in preparation), which was faster and gave very similar results.

Of the samples analyzed for texture, about half were analyzed for coarse sand. The 1 to 2 mm fraction was sieved from the rest of the sand and separated into four categories: crystalline, carbonate, shale, and miscellaneous grains. The proportions of crystalline, carbonate and shale grains were calculated for each sample, neglecting the miscellaneous grains. Crystalline grains are defined for this study as grains composed of quartz and igneous and metamorphic rocks (but not sedimentary rocks such as sandstone); carbonate grains are grains of limestone or dolomite, excluding secondary carbonate; shale grains are mostly gray shale of the Pierre Formation, but other types were also seen, in approximate order of abundance: calcareous, dark gray and white mottled shale, probably of the Niobrara Formation; white shale and brown shale, formation unknown. I analyzed about 450 samples of coarse sand and used about 500 samples analyzed by Moran and others.

Formation boundaries were recognized in the field by field criteria and the gross lithology of the coarse-sand and pebble fractions. Field criteria included color, gross texture, presence of joints, and presence of a boulder lag or a continuous layer of sand and gravel. Field criteria were much less useful in determining formation boundaries in testholes, however. In testholes, formation boundaries were usually recognized by changes in texture and coarse-sand lithology.

The arithmetic mean of the texture and coarse-sand analyses within each unit at each location was calculated; units were correlated by lithologic similarity and position in sequence. This information is summarized on the maps and cross-sections in Appendix A (Plates 1-14).

Of the coarse-sand percentages, shale content is the most distinctive and useful in correlation. Therefore the coarse-sand data is expressed on the maps and cross-sections by two numbers, shale and normalized crystalline. Normalized crystalline is a decimal fraction from zero to 1.00, the number of crystalline grains divided by the sum of crystalline and carbonate grains. Although the normalized crystalline is somewhat more cumbersome to calculate than a simple ratio, such as crystalline grains divided by carbonate grains, it has a conveniently narrow range of variation, instead of from zero to infinity.

Availability of Basic Data

Samples that were collected during this study are on file at the North Dakota Geological Survey in Grand Forks, North Dakota.

Sample numbers and sample locations are on Plate 1 in Appendix A. Film positives and extra copies of the plates are on file at the North Dakota Geological Survey. Basic data used in this report is contained in Appendix B.

CHAPTER II

STRATIGRAPHY

Introduction

The units are described in stratigraphic order (except that all uncorrelated units are described first) from the bottom up. All of the formations described below have been recognized and correlated on the basis of the glacial sediment (till) that they contain. I have generally followed Salomon's (1975) method of assigning fluvial and lacustrine sediments and boulder and cobble accumulations to formations; layers of nonglacial sediment, except those that have been defined as formations, are assigned to the overlying glacial sediment or, if there is none, to the underlying glacial sediment. Boulder pavements are assigned to the underlying glacial sediment, or, if there is none, to the overlying glacial sediment. Boulder pavements are commonly flattened and striated on the upper sides of the boulders. In this case, they are called "soled" boulder pavements, because they were flattened by abrasion at the sole of a glacier.

At many locations, a breccia composed of shale fragments and silt occurs above shale bedrock and below the lowest unit of glacial sediment. In calling this material a "breccia," I do not mean to imply that it is lithified. This material is called "crushed shale" on the sample descriptions of the Air Force engineering testholes. It is assigned to the overlying glacial sediment.

This system is admittedly arbitrary, but it is at any rate consistent. In the future it may be possible to assign nonglacial sediments to formations on the basis of lithology rather than position in sequence, but that is not attempted here.

Unnamed Units

At the base of the section in some holes and surface exposures there are layers of glacial sediment that cannot be correlated with any of the named formations. The thickness and lithology of these scattered intervals are plotted on Plate 14. One unit, found in holes N-1910 and N-1912 (Plate 1, sample location map, Plate 3, cross-section) is lithologically similar to the Vang Formation (described below) but is definitely lower in the section, below the Cando Formation. It is probably correlative with the basal unit of glacial sediment exposed along the Sheyenne River in the Lisbon-Ft. Ransom area which Hobbs and others (in press) referred to as L.-Ft.R.-60.

Another unit, found only in hole N-597 and outcrop N-1622 (Plate 1, Plate 14) has an extremely low shale content for the area. Its position relative to the previously described unit is not known, but it is probably older, since it is less widespread.

Another uncorrelated unit is found between the Vang and the Dahlen Formations in one testhole, NDSWC 8830 (Plate 3). It is sandy and contains very little shale for this area. Because of its geographic position in the extreme west of the study area, and the lack of correlative units elsewhere in the area, I believe it to represent sediment from a glacier which advanced into the area from the west.

Cando Formation (new)

Source of name. The town of Cando, Towner County, North Dakota.

Type area. Towner County.

Type section. I will not designate a type section at this time, since a type section, once selected, can never be changed. The presently-known possibilities are poor choices for various reasons, and I believe that a good type section may be found within a year or two, not necessarily in the present area of study.

Reference sections. Gravel Canyon, gravel pit, N-3006, SW¼NW¼NE¼ sec 36 T163N R59W: 8 to 10 feet of till of the Cando Formation exposed under gravel of the Dahlen Formation.

N-2046, road cut very close to Gravel Canyon, NE¼, NW¼ sec 36 T163N R59W: about 3 feet of till of the Cando Formation exposed under till of the Gardar Formation, which underlies till of the Dahlen Formation.

NDSWC Testhole 8830, SW¼SW¼SW¼ sec 2 T155N R66W: 17 feet of till of the Cando Formation overlain by stratified drift and till of an unnamed unit, overlain by stratified drift and till of the Vang Formation (Plate 4).

Testhole N-1913, NE¼NW¼NE¼ sec 27 T158N R66W: 5 feet of till of the Cando Formation overlies 34 feet of shale breccia of the Cando Formation over shale of the Pierre Formation, and underlies stratified drift and till of the Gardar Formation (Plate 3).

Description. The Cando Formation is composed of pebble-loam (till), stratified drift, and shale breccia. Till of the Cando Formation is olive gray where unoxidized and buff to olive brown where oxidized. The shale content of the coarse sand generally ranges from 55% to 65%. The normalized crystalline ratio generally ranges from 0.55 to 0.70, indicating that crystalline grains generally outnumber carbonate grains in the coarse sand fraction (Plate 13).

Contacts. The Cando Formation rests in place on shale of the Pierre Formation and in places on older, unnamed glacial sediments. The Cando Formation is directly overlain by the Vang Formation in three locations and is overlain by an unnamed unit directly under the Vang Formation in one place. The Cando Formation is also overlain by the Gardar and Dahlen Formations in several places. The Cando Formation is overlain by the Tiber Formation in one testhole, NDSWC 2934, SW¼SW¼SW¼ sec 36 T156N R56W. This relationship provides the only positive evidence that the Cando Formation is older than the Tiber Formation. However, the Cando Formation has never been found to overlie the Tiber Formation.

Extent and Thickness. The Cando Formation is widely preserved in the subsurface in the western part of the area, appearing in all four studied testholes. It is exposed at the surface in several places near the Little South Pembina River (Plate 13) and has been found sporadically at other locations. The till portion of the Cando Formation is generally less than 20 feet thick; too little is presently known to make any further generalizations.

Differentiation. The Cando Formation can be differentiated from the Hansboro, Falconer, and Vang Formations by its greater abundance of shale, from the Tiber Formation by its lesser abundance of carbonate grains, and from the Gardar Formation by its lesser abundance of shale. The Dahlen Formation contains less shale than the Cando Formation in the western part of the area, but more shale than the Cando Formation in the area of the Little South Pembina River. Thus, the Cando Formation can be distinguished from the Dahlen Formation, apart from its stratigraphic position, only by a study of the distribution of shale abundance in the Dahlen Formation (Plate 9).

Origin. The Cando Formation consists of glacial sediment and a considerable amount of stratified drift.

Age and correlation. The age of the Cando Formation is unknown, and it has not been correlated beyond the area of study.

Tiber Formation (new)

Source of name. Tiber Township, Walsh County.

Type area. Central and western Walsh County.

Type section. Surprise outcrop, N-1615, SW¼SW¼NW¼ sec 20 T158N R57W, road cut into the valley of a tributary to the South Branch, Park River. Sixteen feet of till of the Tiber Formation exposed under till and stratified drift (sand and gravel) of the Gardar Formation.

Reference sections. N-3014, NW¼SW¼ sec 20 T158N R57W, road cut across the valley from the type section. About 22 feet of till of the Tiber Formation is exposed; both the top and bottom contacts are covered. A boulder accumulation is exposed 3 feet above the lowest exposed part, but it does not mark a contact, because the material below the boulders is till of the Tiber Formation.

Testhole N-1300, SE¼SE¼SE¼ sec 22 T156N R56W. Till of the Tiber Formation is found from a depth of 200 feet to a depth of 240 feet underneath till of the Gardar Formation.

Testhole N-594, sec 24 T158N R55W. Till of the Tiber Formation is found from a depth of 90 feet to the bottom of the hole at 130 feet, under till of the Vang Formation (Plate 6).

Description. Till of the Tiber Formation is light buff where oxidized and light gray where unoxidized. Iron and manganese stains are absent. Abundant light-colored carbonate pebbles form a lag on outcrop surfaces. The shale content of the coarse sand generally ranges from 45% to 60%, and the normalized crystalline ratio ranges from 0.36 to 0.50, indicating that it contains consistently more carbonate than crystalline grains (Plate 12).

Contacts. The Tiber Formation overlies the Cando Formation in one testhole (mentioned above) and overlies shale bedrock in some places. In most places, however, the bottom of the Tiber Formation is not exposed. The Tiber Formation underlies the Vang Formation in three places, the Gardar Formation in five places, and the Dahlen Formation in two places. Thus, the stratigraphic position of the Tiber Formation relative to the Vang Formation is better established than that of the Tiber Formation relative to the Cando Formation.

Extent and thickness. The Tiber Formation is most extensively preserved at the base of the Pembina Escarpment in Walsh County, northern Grand Forks and southern Pembina County. It is found sporadically in the eastern Drift Prairie, where it probably occupies buried valleys cut into bedrock. The Tiber Formation has not been found in the western Drift Prairie; I am inclined to believe that the cause was nondeposition rather than erosion, because the Vang and Cando Formations and earlier sediments are well-preserved in the area of thick drift between Rolla and Devils Lake. Where the Tiber Formation occurs, it ranges in thickness from 5 to 45 feet.

Differentiation. Till of the Tiber Formation generally contains more carbonate than crystalline grains in the coarse-sand fraction, or in some cases slightly more crystalline than carbonate grains. Till of all other formations generally contains significantly more crystalline than carbonate grains. In some places, till of the Falconer and Gardar Formations contains more carbonate than crystalline grains. But till of the Falconer Formation contains much less shale, and till of the Gardar Formation more shale, than does till of the Tiber Formation.

Origin. The Tiber Formation consists of glacial sediment and a small amount of lacustrine sediment. The glacier that deposited the Tiber Formation advanced from the north-northeast, picking up abundant carbonate from the northern Red River Valley.

Age and correlation. The age of the Tiber Formation is not known. It is correlated with a unit of glacial sediment exposed along the Sheyenne River Trench from Lisbon to Fort Ransom (Hobbs and others, in press). It is more tenuously correlated with unnamed Unit 2 (Harris, 1975) in northwestern Minnesota. The Tiber Formation is equivalent to Unit D of Salomon (1975).

Vang Formation (new)

Source of name. Hamlet of Vang, Cavalier County.

Type area. Eastern Cavalier County.

Type section. Sprinke Site, N-2040, NE¼SW¼ sec 26 T163N R58W, road cut into a tributary valley of the Pembina River. Twenty-two feet of till of the Vang Formation are exposed under till of the Gardar Formation. A cobble and boulder accumulation occurs at the top of the Vang Formation. The bottom of the Vang Formation is not exposed at this outcrop.

Reference sections. Testhole N-2338, sec 27 T163N R58W, less than a mile from the type section. Seventeen feet of till and 6 feet of shale breccia of the Vang Formation overlies shale of the Pierre Formation and underlies 8 feet of till of the Dahlen Formation.

Testhole N-1910, SE¼ SW¼SE¼ sec 11 T163N R69W. This hole contains 15 feet of till of the Vang Formation, overlain by till of the Gardar Formation and underlain by till of the Cando Formation (Plate 3).

Description. At its type section and the nearby reference section, the till of the Vang Formation is sandy, buff where oxidized and light gray where unoxidized. Pebbles and cobbles of crystalline rocks are fairly abundant. At other locations, the till of the Vang Formation is not as sandy, but has the same general appearance. Coarse sand in the till of the Vang Formation contains little shale (from 25% to 45%) (Plate 11). Crystalline grains are considerably more common than carbonate grains; the normalized crystalline ratio generally ranges from 0.60 to 0.75 (Plate 11).

Contacts. The Vang Formation directly overlies shale of the Pierre Formation in six places, overlies the Cando and Tiber Formations in three places each, and overlies uncorrelated sediments in four places. In three places, the bottom of the Vang Formation was not reached. The Vang Formation is at the surface at one location; of the remaining locations it is overlain by the Dahlen and Gardar Formations in approximately equal numbers of locations. The Vang

Formation is not directly overlain by the Hansboro or Falconer Formations at any known location.

Extent and thickness. The Vang Formation occurs sporadically over the entire area of study. It is generally fairly thin, 20 feet or less in thickness, but at NDSWC 8830, near Churchs Ferry, 40 feet of till of the Vang Formation overlies 110 feet of stratified drift of the Vang Formation (Plate 4).

Differentiation. Till of the Vang Formation can be distinguished from till of the Dahlen, Gardar, Tiber, and Cando Formations by its lesser shale content. Till of the Vang Formation can be distinguished from till of the Hansboro Formation by its greater shale content and stratigraphic position and from till of the Falconer Formation by its stratigraphic position.

Origin. The Vang Formation contains glacial sediment and, locally, large amounts of stratified drift. The glacier that deposited till of the Vang Formation advanced from the east and northeast, bringing abundant crystalline sand from the Canadian Shield.

Age and correlation. The age of the Vang Formation is not known. It is correlated with a layer of glacial sediment exposed in the Sheyenne River Trench (Hobbs and others, in press), and with the Marcoux Formation in northwestern Minnesota (Harris, Moran, and Clayton, 1974). The Vang Formation is generally equivalent to Units B and C of Salomon (1975).

Gardar Formation (Salomon, 1975)

Description. Till of the Gardar Formation is olive brown where oxidized and olive gray where unoxidized. It is generally strongly jointed and stained by oxides of iron and manganese. Shale fragments are very abundant; the shale content of the coarse sand generally ranges from 60% to 90% with extreme values of 38% and 95% (Plate 10). Crystalline grains are generally more common than carbonate grains. The normalized crystalline ratio generally ranges from 0.50 to 0.75.

Subdivision. Along the base of the Pembina Escarpment, from Edinburg to the southern edge of the study area, the Gardar Formation can be divided into an upper and a lower member. The lower member can be distinguished by its shale content, which is generally 10% to 15% less than the upper member (Plate 10). The upper member forms the full thickness of the Gardar Formation outside this area, and is equivalent to the Gardar of Salomon (1975). The lower member is equivalent to Salomon's Unit A. In places, the upper member is absent, and the lower member is recognized by its lower shale content relative to nearby samples of the upper member (Plate 10).

Contacts. The Gardar Formation generally rests on older glacial sediments in the Red River Valley and the western part of the Drift Prairie and on shale bedrock in the eastern part of the Drift Prairie and along the Pembina Escarpment. In places, such as N-2040, the type section of the Vang, the Gardar Formation rests on a soled boulder pavement at the top of an older layer of glacial sediment. The Gardar Formation contains a soled boulder pavement at its base in some places where it rests on shale of the Pierre Formation. The Gardar Formation occurs sporadically at the surface, but is generally overlain by the Dahlen Formation, where it commonly contains a soled cobble and boulder pavement at its top.

Extent and thickness. The Gardar Formation is extensively distributed over the study area, but it is absent in several broad areas (Plate 10). The Gardar Formation is much more commonly found than any older formation (Plates 10, 11, 12 and 13), which indicates a period of considerable erosion before the deposition of the Gardar Formation. The thickness of the Gardar Formation is variable, but some generalizations can be made. Till of the Gardar Formation is generally less than 15 feet thick over the Drift Prairie and the Pembina Escarpment and from 40 to over 100 feet thick at the base of the Pembina Escarpment, particularly in the southern part of the study area (Plate 10).

Differentiation. Till of the Gardar Formation can be differentiated from till of any other formation by its abundant shale. Although some samples of till of the Gardar Formation contain less abundant shale than some samples of till from other formations, till of the Gardar Formation contains more shale than till of any other formation at the same location. Shale abundance is different from place to place in each formation; the general pattern is strong decrease eastward from the Pembina Escarpment and small, variable decrease westward from the Pembina Escarpment.

Origin. The Gardar Formation is composed of glacial sediment and some stratified drift. The ice that deposited the glacial sediment of the Gardar Formation advanced from the northwest, as indicated by striations on soled boulders beneath its base.

Age and correlations. The age of the Gardar Formation is not known, but, like all the underlying formations, it is older than Late Wisconsinan. The Gardar Formation may have been deposited during the Napoleon Glaciation (Moran and others, in press). Clayton (1966) has suggested that the Napoleon Glaciation was early Wisconsinan. The Gardar Formation is correlated with glacial sediment (L.-Ft.R.-30) exposed along the Sheyenne River Trench between Lisbon and Ft. Ransom (Hobbs and others, in press), and with the St. Hilaire Formation in northwestern Minnesota (Harris and others, 1974) on the basis of shale abundance.

Dahlen Formation (Salomon, 1975)

Description. Till of the Dahlen Formation is generally light brown where oxidized and medium to olive gray where unoxidized. It tends to be soft and friable to a depth of several feet below the surface and harder and blocky below. Iron- and manganese-oxide stains are common in areas where till of the Dahlen Formation contains abundant shale. Shale content of the coarse sand of the till generally ranges from 40% to 80% (Plate 9). This range is uncommonly large. Crystalline grains are more common than carbonate grains in the coarse sand: the normalized crystalline ratio generally ranges from 0.55 to 0.65 (Plate 9).

Contacts. The Dahlen Formation rests most commonly on till of the Gardar Formation. Where the Gardar Formation is absent, the Dahlen Formation rests on shale bedrock or older glacial sediments. A soled boulder pavement is commonly observed at the top of the Gardar Formation or older formations overlain by till of the Dahlen Formation. The Dahlen Formation commonly contains a boulder pavement at its base where it overlies shale bedrock. Striations on these boulder pavements are generally aligned northwest-southeast. The Dahlen Formation is overlain by the Falconer Formation in parts of the Red River Valley, in some places separated from the Falconer Formation by laminated lake sediment of the Wylie Formation (Harris and others, 1974). In parts of the western Drift Prairie, the Dahlen Formation is overlain by till of the Hansboro Formation.

Extent and thickness. The Dahlen Formation covers virtually the entire area. The till of the Dahlen Formation is generally from 25 to 40 feet thick in the southern and western parts of the Drift Prairie, and generally from 5 to 15 feet thick in the northeastern part of the Drift Prairie and along the Pembina Escarpment. In the Red River Valley, till of the Dahlen Formation generally ranges in thickness from 15 to 50 feet (Plate 9). In areas where the Dahlen Formation is generally thin, particularly along the Pembina Escarpment, till of the Dahlen Formation is absent in places or may be so thin that it is obscured by the soil horizon. In these places, the boulder pavement beneath the Dahlen Formation may be at the surface or covered by only a thin soil.

In general, where till of the Dahlen Formation forms the surface sediment, the Dahlen Formation is generally thickest where the surface hummocks are highest, and is generally thin in areas of flat surface topography. Although exceptions exist, this general observation supports the model developed by Clayton and Moran (1974) in A Glacial process-form model. This subject will be more fully discussed below.

Differentiation. Till of the Dahlen Formation can be distinguished from till of the Vang, Falconer, and Hansboro Formations by its greater abundance of shale, from till of the Gardar Formation by its lesser abundance of shale, and from till of the Tiber Formation by its greater abundance of crystalline grains relative to carbonate grains. Till of the Dahlen Formation can be distinguished from till of the Cando Formation by stratigraphic position and the distribution of shale abundance in the Dahlen Formation (Plate 9).

Origin. The Dahlen Formation consists of glacial sediment and a small amount of fluvial and lacustrine sediment. The glacier that deposited the till of the Dahlen Formation advanced from the northwest, as indicated by striations on the boulder pavement, alignment of drumlins, and alignment of washboard moraines.

Age and correlations. The Dahlen Formation includes the deposits of the main Late Wisconsinan glaciation, which has been called the Lostwood Glaciation by Clayton (1972). The Dahlen Formation extends well to the south of the study area and is exposed along the Sheyenne River Trench (Hobbs and others, in press), where it is informally known as L.-Ft.R-20. The Dahlen Formation is correlated with the upper part of the Red Lake Falls Formation (Harris and others, 1974) on the basis of shale content, but not with the lower part of the Red Lake Falls formation, which contains very little shale and was probably derived from a northeastern rather than northwestern source.

Hansboro Formation (new)

Source of name. The village of Hansboro, Towner County.

Type area. The area east of the Turtle Mountains in northern North Dakota.

Type section. I will not designate a type section for the Hansboro Formation at this time for the same reasons that I have not designated a type section for the Cando Formation; the present possibilities are undesirable and a better location may soon be found.

Reference sections. Testhole N-1913, NE¼NW¼NE¼ sec 27 T158N R66W: 18 feet of clay of the Hansboro Formation underlain by 13 feet of till of the Hansboro Formation underlain by 15 feet of sand and silt of the Hansboro Formation, underlain by till of the Dahlen Formation (Plate 3).

N-3013, road cut and eroded ditch, SW¼NW¼NW¼ sec 30 T155N R67W: 13 feet of till of the Hansboro Formation overlies till of the Dahlen Formation; the contact is obscure.

Description. The Hansboro Formation consists of pebble-loam (till) and stratified drift. Till of the Hansboro Formation is similar in appearance to till of the Dahlen Formation: buff where oxidized, light gray where unoxidized, generally fissile and lacking iron-stained joints. The shale content of till of the Hansboro Formation is sparse, ranging from 17% to 27% in the coarse-sand fraction (Plate 8). Crystalline sand grains are considerably more common than carbonate grains: the normalized crystalline ratio ranges from 0.62 to 0.69 (Plate 8).

Contacts. In all the locations where it has been studied, the Hansboro Formation rests directly on the Dahlen Formation. No formation has been observed resting on the Hansboro Formation.

Extent and thickness. The Hansboro Formation occurs widely in the western part of the Drift Prairie. Its boundaries are not well defined because of a scarcity of data points in the western half of the Drift Prairie. Where it occurs, the till portion of the Hansboro Formation is less than 15 feet thick (Plate 8).

Differentiation. The Hansboro Formation can be distinguished from the Cando, Tiber, Vang, Dahlen, and Gardar Formations by the lesser abundance of shale in the till portion. The Hansboro Formation can be distinguished from the Falconer Formation by its geographic position: the Hansboro Formation occurs only in the western part of the study area; the Falconer Formation occurs only in the eastern part. There is a considerable area in the central part of the study area where neither occurs.

Origin. The Hansboro Formation consists of glacial sediment and a minor amount of stratified drift. Till of the Hansboro Formation, while quite low in shale for the present study area, was mapped by Deal (1971) as "Shale-rich 'till' east of the Turtle Mountains." Deal indicates that the ice that deposited this till flowed south along the east side of the Turtle Mountains. To the west of the Turtle Mountains, the bedrock is composed of sandstone and siltstone, and the till in that area contains very little shale.

Age and correlation. The age of the Hansboro Formation is not known, but it is younger than the underlying Dahlen Formation. It was probably deposited by a readvance of the retreating late Wisconsinan glacier. This readvance may have corresponded to the readvance that deposited the Falconer Formation. My feeling is, however, that the Hansboro Formation is older than the Falconer Formation, because it covers a much larger area at a higher topographic position. It is possible that the readvance that deposited the Hansboro Formation was a reactivation of stagnant ice from the glacier which deposited the Dahlen Formation. This would explain why the eastern edge of the Hansboro Formation does not correspond to any presently-known ice-marginal position.

The informal unit L.-Ft.R.-10, exposed above the Dahlen Formation in the Sheyenne River Trench (Hobbs and others, in press), is similar to the Hansboro Formation in shale abundance and in stratigraphic position. At present, too little is known of the area in between to permit a correlation.

Falconer Formation (Harris and others, 1974)

Description. The Falconer Formation consists of pebble-loam (till) and a minor amount of sand and gravel. Till of the Falconer Formation is light brown where oxidized and medium gray where unoxidized. At its western margin along the Edinburg Moraine, till of the Falconer Formation is similar in appearance to the underlying Dahlen Formation; to the east, where it is known from the subsurface, the till becomes much less sandy, contains much less shale, and more carbonate pebbles (Plate 8).

Contacts. Along its western margin, the Falconer Formation rests directly on the Dahlen Formation in places; the two formations are separated by a few feet of laminated clay of the Wylie Formation in other places. Farther east, the Wylie Formation separates the Dahlen and Falconer Formations at almost every location. The Falconer Formation is commonly overlain by obscurely laminated lacustrine clay of the Brenna Formation (Harris and others, 1974) in the deeper parts of glacial Lake Agassiz and by shoreline sand and gravel near the margin. In places within the general area of occurrence of the Falconer Formation, the Falconer Formation is absent (Plate 8), probably because of erosion by waves.

Extent and thickness. The Falconer Formation generally extends from the eastern boundary of the study area to the Edinburg Moraine, or, north of Edinburg, approximately to the Pembina Escarpment. However, till of the Falconer Formation has been found in testholes more than a mile west of the Edinburg Moraine, such as N-1305, east of Fordville (Plate 8). This indicates that, while the moraine may mark the general extent of the glacier which deposited the Falconer Formation, it does not mark the greatest extent.

The full thickness of the Falconer Formation under the Edinburg Moraine has not been determined, but it is probably greater than 25 feet. In the southern part of the study area, the Falconer Formation is consistently about 20 feet thick where it is present (Plate 8).

Differentiation. Till of the Falconer Formation can be distinguished from till of the Cando, Tiber, Gardar, and Dahlen Formations by its lesser shale content, although the difference between the Dahlen and the Falconer Formations is not very great in some places. Till of the Vang Formation can be distinguished from till of the Falconer Formation primarily by stratigraphic position. The Hansboro Formation can be distinguished from the Falconer Formation by geographic position.

Origin. The Falconer Formation consists of glacial sediment and some fluvial sediment. The glacier which deposited the pebble-loam of the Falconer Formation advanced from the north up the axis of the Red River Valley.

Age and correlations. The Falconer Formation was deposited by a late readvance of the retreating late Wisconsinan glacier. Its age is greater than 13 500 B.P., based on radiocarbon dates in North Dakota (Moran and others, 1974). The Falconer Formation is laterally equivalent to the Huot Formation in northwestern Minnesota (Harris and others, 1974).

CHAPTER III

DISCUSSION

Glacial Shearing

The effects of glacial shearing have complicated the interpretation of the stratigraphy in the area of study. In the preceding section on stratigraphy, it has been assumed for the sake of simplicity that the units named are always in their original depositional order. However, glacial shearing has sometimes brought portions of an older formation to rest on a younger formation. In testhole N-601 (Plate 5) for example, the uppermost sample (5.0 to 6.5 feet) has the composition of the Gardar Formation, samples from 10 to 33 feet have generally the composition of the Dahlen Formation, and samples from 33 to 42.5 feet have the composition of the Gardar Formation. (Till samples above 5 feet in depth were not recovered from Air Force engineering test borings; thus, whatever material that occurs in the first sample is assumed to extend to the surface, for the purpose of making maps and cross-sections. Similarly, since complete cores were not recovered, formation boundaries were often drawn halfway between sampled intervals).

Since repetition of section is a characteristic of thrust faulting, the above situation could justifiably be treated as a thrust fault. Harris and others (1974) described the Oppornockity

Section (exposed in the Red Lake River Trench) in that way, though they did not specifically call it an example of thrust faulting.

Masses of shale breccia thrust up from below are rather common in the Dahlen Formation. For example, Texthole N-2341 (Plate 2) reveals two blocks of shale breccia within the Dahlen Formation. In this case, shear ridges can be seen on the surface on airphotos, trending northeast-southwest.

Relationship Between Thickness and Surface Morphology of the Dahlen Formation in an Area Between Langdon and the International Boundary

Introduction. The thickness of the Dahlen Formation is quite variable over the area of study (Plate 9) as is the surface morphology. The thickness observations over the whole area are too scattered to make detailed correlations between thickness and morphology, so I chose a smaller area for more detailed study. The smaller area comprises two 15 minute quadrangles extending from the town of Langdon north to the International Boundary (Plate 15). This area is referred to below as the "Langdon area."

Four types of morphology are found within this area, excluding postglacial erosional morphology: (1) shear ridges, (2) drumlins, (3) collapsed superglacial morphology, and (4) flat plains (Plate 15).

Clayton and Moran (1974) have presented a glacial form-process model that deals with the origin of various glacial land forms. According to their model, shear ridges are of two kinds: (1) subglacial features formed by thrusting and composed of preadvance sediment veneered by last-advance glacial sediment and (2) englacial features (washboard moraine) composed of glacial sediment of the last advance. Drumlins are longitudinal shear marks formed at the glacier sole, composed of pre-advance sediments veneered by glacial sediment of the last advance. Collapsed superglacial morphology takes the form of hummocks and closed depressions with no strong preferred orientation, originated by mudflows down the sides of sinkholes on a stagnant melting glacier. The origin of flat topography is not specifically dealt with in the model. Inferentially, flat topography is found in areas which were relatively flat before the last glacial advance, suffered little or no subglacial erosion, on which the superglacial sediment is thin to absent. The model explicitly ignores the existence of subglacial till, which was held to be lithologically indistinguishable from englacial or superglacial sediments.

In general, the thickness of glacial sediment of the last advance, according to the model can be summarized as follows: in areas of subglacial thrusting, the glacial sediment of the last advance should be variable in thickness and should include large blocks of pre-existing sediment; in areas of washboard moraine, the glacial sediment of the last advance should be thin, not much thicker than the heights of the washboard ridges; in areas of superglacial collapse topography the thickness of the glacial sediment of the last advance should be about as great as the relative relief. In areas of drumlins and flat topography, the glacial sediment of the last advance should be thin and uniform.

I am assuming that the thickness of the Dahlen Formation in this area is the same as the thickness of glacial sediment of the last advance. I assume this for the following reasons. No formation has been observed to overlie the Dahlen Formation in this area. The

Dahlen Formation in this area is composed largely of glacial sediment, containing only minor stratified drift and shale breccia. For the purpose of this detailed study, shale breccia at the base of the Dahlen Formation is not included in its thickness.

The thickness of the Dahlen Formation, in feet, has been plotted at numerous points and contoured (Plate 15). The contours must be regarded as approximate, because the thickness can change greatly in a short distance, even within a single outcrop. Where space permits, and where a significant difference exists, both a minimum and a maximum figure are given; otherwise, the arithmetic mean is given. Surface exposures are marked X; auger holes are marked 0, testholes are marked 0 with a solid center. Where the base of the Dahlen Formation was not observed or determined, a "greater than" (>) symbol was placed before the number indicating the greatest thickness observed.

In the area of thin drift, most of the holes were drilled with a hand-held power auger. They were drilled until the auger stopped, either at bedrock (or a large boulder) or in water-saturated sediment below the water table. It was possible to distinguish holes which stopped at rock from those that bogged down in mud--the latter were marked with a "greater than" symbol (>). In the area of thin drift, the Dahlen Formation generally rests on shale of the Pierre Formation rather than older glacial sediment.

Where the drift cover was more than 10 feet thick, the auger could not be used; some testholes with core samples were available. By the use of the core samples and driller's logs, it was possible to distinguish till of the Dahlen Formation from older glacial sediments.

<u>Area of shear ridges</u>. Low-relief washboard moraine, with ridges about 3 feet high and trending northeast-southwest, dominate the eastern part of the area of shear ridges. The ridges are concave to the northwest. In this part of the area, the Dahlen Formation is locally absent; in places it is as much as 20 feet thick, but in most places it is from 5 to 10 feet thick. This is somewhat thicker than would be expected from the model; the discrepancy probably lies in the model's failure to consider subglacial till. In order to reconcile the model with the observed thicknesses, one must postulate a layer of subglacial till, uniformly about 6 feet thick. However, it should be emphasized at this point that in dozens of exposures in the Langdon area, no visual or lithologic break was observed, corresponding to the boundary between subglacial and superglacial till.

In the western part of the area of shear ridges, the ridges are higher and broader but less well-defined. According to the model, they are shear ridges partially masked by collapsed superglacial sediment. There are only two thickness observations in this part of the area, as it is undissected and the drift was too thick to drill through with the auger. In one testhole, the Dahlen Formation is 20 feet thick, underlain by 6 feet of till of the Gardar Formation, underlain by shale (based on driller's log and visual examination of the samples without grain counts). In the other testhole, the Dahlen Formation is 104 feet thick (N-591, Plate 4). A block of shale breccia is included in this thickness, indicating considerable shearing activity, because shale breccia is usually found at the interface between shale bedrock and glacial sediment. Just off the map sheet to the west, testhole N-2341

(Plate 2), previously mentioned, penetrates two large masses of shale breccia that have been sheared up into the Dahlen Formation.

Area of collapsed superglacial morphology. The distinction between this area and the western part of the area of shear ridges is that the area of collapsed superglacial morphology shows no strong preferred orientations. There are some vague features aligned to the northeast-southwest that may be partly buried shear ridges and some slightly sinuous ridges trending northwest-southeast that are probably eskers. The western part of the area of shear ridges contains eskers and some collapsed superglacial topography, also, so the two areas are gradational to one another.

The area of collapsed superglacial topography is little-dissected by streams; consequently thickness observations are sparse and are commonly minimum figures. The available data indicate, however, that the thickness of the Dahlen Formation ranges generally from 10 feet to 20 feet.

The relative relief of the area is generally 10 to 15 feet. According to the model, the thickness of the superglacial sediment should average 10 to 15 feet; the predicted value fits the observed value fairly well; a slightly better fit would result from postulating a uniform layer of about 5 feet of subglacial till underlying the superglacial sediment.

Area of drumlins. The area of drumlins falls into three sub-areas: (1) a large area of streamlined hills and elongated depressions north and east of Langdon, in which the topography is aligned northwest-southeast, (2) a small area west of Langdon with similar topography, and

(3) a small area to the east of the subarea (1) in which the alignment is northeast-southwest.

The hills are composed of shale of the Pierre Formation, mantled by glacial sediment of the Dahlen Formation. The Dahlen Formation is commonly 6 to 7 feet in thickness (Plate 15) with extreme values of 3 and 18 feet. The thickness of the Dahlen Formation is significantly less than the relative relief, which ranges generally from 15 feet to 40 feet.

All of the drumlins were formed during the last ice advance except the drumlins which are aligned to the northeast-southwest. They are lower and less steep than the other drumlins and are composed of shale with a thin (3 feet) cover of till of the Dahlen Formation. Judging by their orientation, they must have been formed during the glacial advance that deposited the Vang or the Tiber Formation.

Two of the highest and steepest drumlins (sections 1 and 2, about 1 mile north-northeast of Langdon, Plate 15) are just southeast, and thus downglacier, from depressions of about the same size as the hills. The hills are probably blocks of bedrock which were picked up by the glacier, transported about a mile, dropped, and then streamlined by abrasion. Bluemle (1970) has reported similar phenomena in Sheridan and McLean counties, North Dakota.

Hummocks of the sort found in areas of superglacial collapse topography are absent or very low in the area of drumlins. This agrees with the prediction of the form-process model that superglacial sediment is thin to absent in areas of drumlins. Most of the thickness of the Dahlen Formation in this area is probably composed of subglacial till. In fact, the thickness of the Dahlen Formation in the area of drumlins is about the same as the thickness of subglacial till that must be postulated in the area of washboard moraines and collapsed superglacial topography in order to satisfy the model.

Area of Flat plains. The area of flat plains most closely resembles the area of drumlins, except that there is less relief and little or no alignment of topography. Superglacial collapse hummocks are also absent. According to the model, superglacial sediment should be thin to absent in this area.

The thickness of the Dahlen Formation generally ranges from 6 feet to 10 feet in this area (Plate 15), with extreme values of 2 feet and 60 feet. The latter figure is quite incongruent with the general thickness in this area. Since there are no certain thickness observations closer than 4 miles in any direction, it is not known whether the 60 feet observation represents a buried valley or a broad area of thick drift. I think that a buried valley is a more probable explanation; this location is not far from the Pembina Escarpment, and during every ice-free period there must have been numerous streams cut through the Escarpment. Small buried valleys can be seen now in the area of the Pembina Escarpment where they have been cut through at an angle by a modern valley. If the hole in question does indeed penetrate a buried valley, it must be an old one. The Dahlen Formation overlies till and silt of the Tiber Formation in the hole, so the valley must have been cut prior to the ice advance which deposited the Tiber Formation.

All or nearly all of the thickness of the Dahlen Formation in the area of flat plains is subglacial till, as is the case in the area of drumlins. The main difference between the area of drumlins and the area of flat plains was whether or not the glacier was eroding at its sole. In general, the area of drumlins is topographically higher than adjacent areas of flat plains. This may explain the difference in erosion. Another possibility suggested by the model is that the pore-water pressure under the glacier sole was dissipated in the area of drumlins, causing the weight of the glacier to rest on the substrate and causing erosion. Under the areas of flat plains, the pore-water pressure was not dissipated, the glacier's weight was supported by the water, and little erosion occurred. There is no way of testing this hypothesis with the data at hand.

Conclusions. In general, the glacial form-process model fits the observed morphology and thickness of the Dahlen Formation in the Langdon area if a relatively uniform layer of subglacial till about 5 feet thick is postulated to cover the entire area.

Summary

Repeated Pleistocene glaciations of northeastern North Dakota have left numerous layers of glacial sediment and glacier-related fluvial and lacustrine sediment. On the basis of present knowledge of the area, some of these sediments can be grouped into seven distinct formations: The Cando, Tiber, Vang, Gardar, Dahlen, Hansboro and Falconer Formations. Further study of the area will make it possible to define several more formations from the at present uncorrelated sediments at the base of the section.

The general distribution of these formations is as follows. The western part of the Drift Prairie is underlain by sediments of the Hansboro, Dahlen, Gardar, Vang, and Cando Formations and considerable drift from unnamed units. The eastern part of the Drift Prairie and the Pembina Escarpment is underlain by sediments of the Dahlen and Gardar

Formations resting on bedrock, underlain locally by sediments of other formations and unnamed units. The Red River Valley is underlain by sediments of the Falconer, Dahlen, Gardar, Vang, and Tiber Formations, overlain by sediments of glacial Lake Agassiz.

The age of the Hansboro, Falconer, and Dahlen Formations is late Wisconsinan. The age of the Gardar Formation is probably early Wisconsinan. The ages of the underlying formations are unknown, but are probably pre-Wisconsinan.

The study of the Pleistocene stratigraphy is of value for the purpose of conducting groundwater studies in this area. The till and lacustrine sediments of these formations are aquitards; the fluvial sediments are aquifers. The fluvial sand and gravel generally occurs in the lower part of formations, as defined. Groundwater will tend to flow within a formation unless sand and gravel from two formations are in contact. For example, sand and gravel of the Dahlen Formation is more likely to be in hydrologic continuity with sand and gravel of the Dahlen Formation at another location than with sand and gravel of the Gardar Formation. Thus, in a sequence of sediments, glacial sediments are at the same time aquitards and marker beds.

A second contribution of the present study to future groundwater studies is the testing and general confirmation of the Clayton-Moran form-process model, which provides a means of predicting the thickness of the surface layer of glacial sediment on the basis of surface morphology, which can be rapidly determined by a study of existing topographic maps and airphotos. Using the model, it is possible to determine the thickness of the surface layer of glacial sediment over large areas, with relatively few testholes for confirmation. This capability can be used for preliminary assessment of waste-disposal sites, both liquid (lagoons) and solid (sanitary landfills).

APPENDIX A

FURTHER EXPLANATION OF MAPS AND CROSS-SECTIONS

Plate 7, Location map for samples and cross-sections: X represents surface exposures, 0 represents testholes (on this and all other maps). Numbers beginning with N are part of the North Dakota Geological Survey sample numbering system. Numbers without a prefix (there are only a few of these) are part of the North Dakota State Water Commission sample numbering system. Dark lines represent the trace of the cross-sections.

Plate 8, Thickness and lithology of the Falconer and Hansboro Formations: sample locations in the east part of the map are of the Falconer Formation, in the west part, of the Hansboro Formation. Numbers above the sample location symbols represent the thickness, in feet, of the till part of the formation at that location, on this and all other maps. Numbers below the symbols represent the lithology of the coarse sand of the till at that location (the arithmetic mean of all samples). At a given location, the number to the right is the percentage of shale; the number to the left is the normalized crystalline ratio, explained in the Introduction.

Shale percentage of the Falconer Formation is contoured; the contour interval is 10%. The purpose of the contour lines is to make the trend of shale abundance more visible. The shale percentage of the Hansboro Formation is not contoured.

Plate 9, Thickness and lithology of the Dahlen Formation; the symbols are the same as on the preceding map, except that the symbols "greater than" (>) and "less than (<) are placed before the thickness figures in some places.

Plate 10, Thickness and lithology of the Gardar Formation: the symbols are the same as on the preceding map except that the thickness and lithology of the lower member is symbolized to the right of the sample location symbol, enclosed by a circle. In places where the upper member is absent and the lower member is present, the thickness and lithology of the lower member is symbolized in the same manner as the upper member, with an asterisk to the right. The contour lines on this map represent only the upper member.

In a number of locations on Plate 10, the Gardar Formation is marked "absent." This was done so that the reader could distinguish between areas in which the Gardar Formation is known to be absent and areas in which there is no information.

Plate 11, Thickness and lithology of the Vang Formation: the symbols are the same as on the preceding map, except that the Vang Formation is not marked where it is absent, because it is absent in a large majority of locations.

Plate 12, Thickness and lithology of the Tiber Formation: the symbols are the same as on the preceding map, except that the shale abundance is not contoured.

Plate 13, Thickness and lithology of the Cando Formation: the symbols are the same as on the preceding map.

Plate 14, Thickness and lithology of various uncorrelated units: the symbols are the same as on the preceding map, except that, where two different uncorrelated units are found in the same hole, the thickness and lithology of the lower unit is symbolized to the right of the sample location symbol, in the same manner that the lower member of the Gardar Formation was symbolized.

All of the units on this map are stratigraphically lower than the named and correlated units presented in Plates 8-13. One uncorrelated unit, found in NDSWC 8830 (Plate 3) is not included on this map because its stratigraphic position is between the Dahlen and Vang Formations.

Plate 15, Thickness and surface morphology of the Dahlen Formation in an area from Langdon, North Dakota, to the International Boundary: the symbols are explained in the discussion.

APPENDIX B

DATA SUMMARY AND BASIC DATA

Basic data-textures and coarse-sand analyses used in the compliation of this report are contained in a pocket with this report. The information is in ascending order of location numbers, all of which are n-numbers, except 8830 and 8780, which are NDSWC numbers. Within one location, samples are in ascending order of sample number or letter, which may be in normal or reverse order of depth. Data from locations in which only one sample was taken is not included; the coarse-sand data can be directly read from the map of the appropriate formation. Where samples are of intervals, the top of the interval is given as the depth. The figures for texture and coarse-sand lithology have been rounded to the nearest whole percentage, which has caused some small discrepancies. For example, the percentages sometimes add up to 99% or 101%.

The texture and coarse-sand lithology of each of the formations are summarized in Table 1. The figures are not averages of all of the existing data, because any such average would be highly sensitive to the sampling pattern. In general, more samples were taken from shale-rich areas than shale-poor areas. The figures can be described as "area-weighted medians" and are not intended to be exact, but to present the characteristics of each formation in as condensed a form as possible.

TABLE 1

TEXTURE AND COARSE--SAND LITHOLOGY OF GLACIAL SEDIMENTS (TILL) IN THE AREA OF STUDY

Formation	Sand	Silt	Clay	Crystalline	Carbonate	Shale
Hansboro Formation	28	38	34	50	27	23
Falconer Formation	29	33	38	42	34	24
Dahlen Formation	29	44	27	26	19	55
Gardar Formation	32	42	26	10	8	82
Vang Formation	34	35	31	40	25	35
Tiber Formation	27	38	35	21	28	51
Cando Formation	35	41	24	25	16	59

TABLE 1

TEXTURE AND COARSE--SAND LITHOLOGY OF GLACIAL SEDIMENTS (TILL) IN THE AREA OF STUDY

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Vang Formation	34	35	31	40	25	35
Tiber Formation	27	38	35	21	28	51
Cando Formation	35	41	24	25	16	59

Texture figures are percentages of total sand, silt and clay, excluding gravel. Coarse-sand lithology figures are percentages of total crystalline, carbonate and shale, excluding miscellaneous grains. Figures are area-weighted medians--considerable variation from the median exists in all formations.

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PLATE I LOCATION MAP FOR SAMPLES AND CROSS-SECTIONS

PLATE 2 STRATIGRAPHIC CROSS SECTION FROM ROLLA TO WALHALLA

PLATE 3 STRATIGRAPHIC CROSS SECTION FROM ROLLA TO CHURCHS FERRY

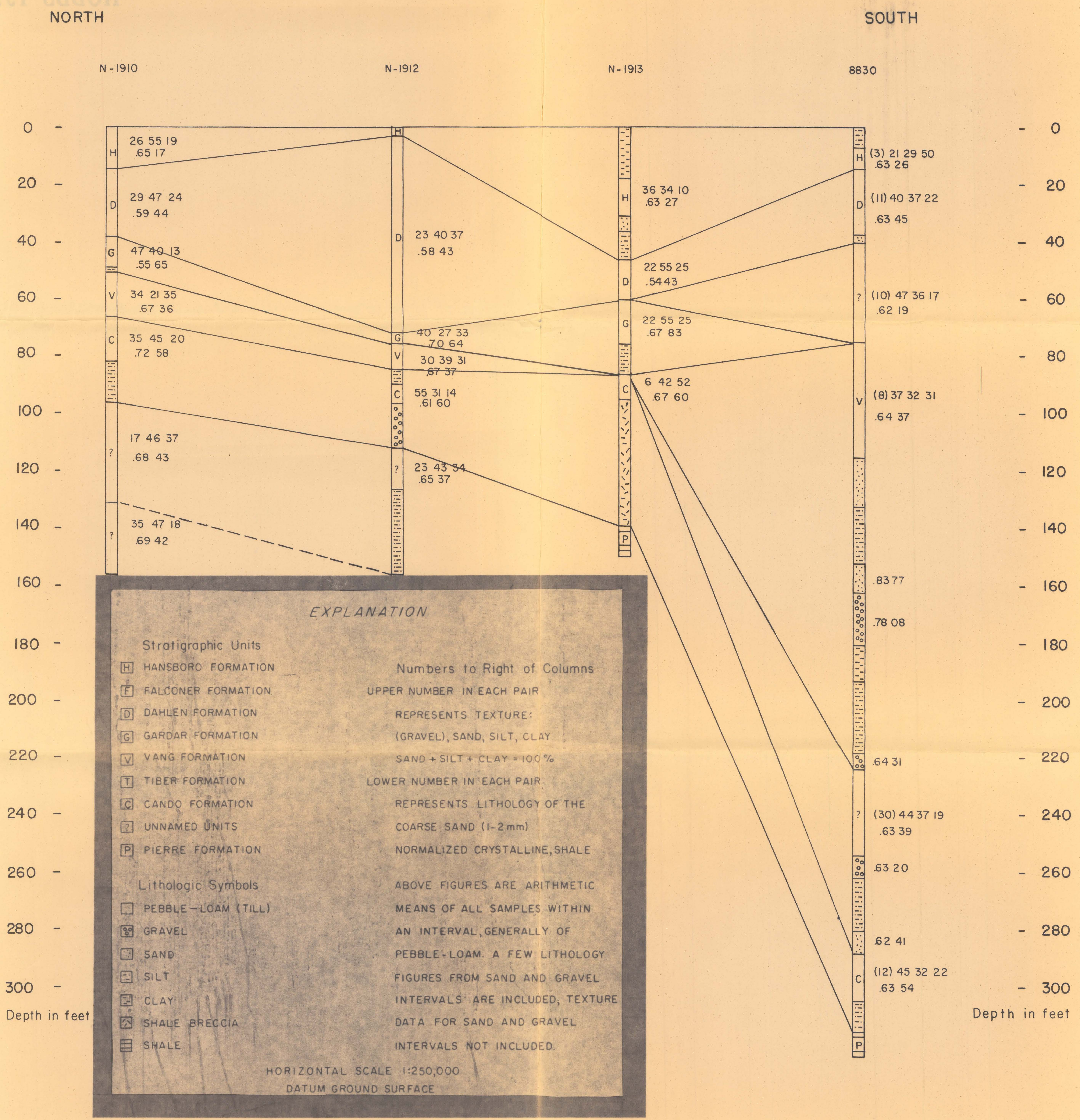


PLATE 4 STRATIGRAPHIC CROSS SECTION FROM CHURCHS FERRY TO MT. CARMEL

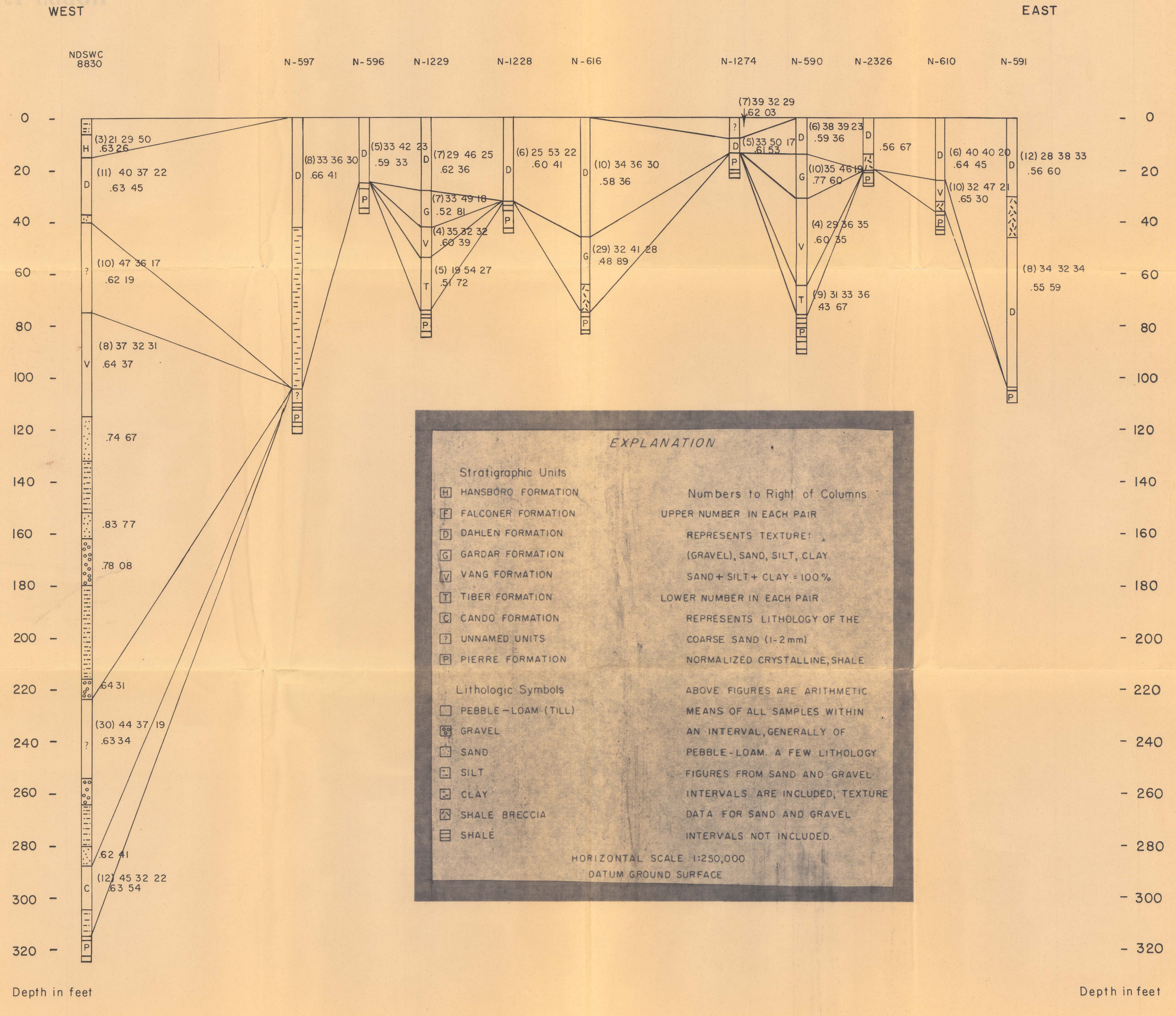


PLATE 5 STRATIGRAPHIC CROSS SECTION FROM CHURCHS FERRY TO ARDOCH

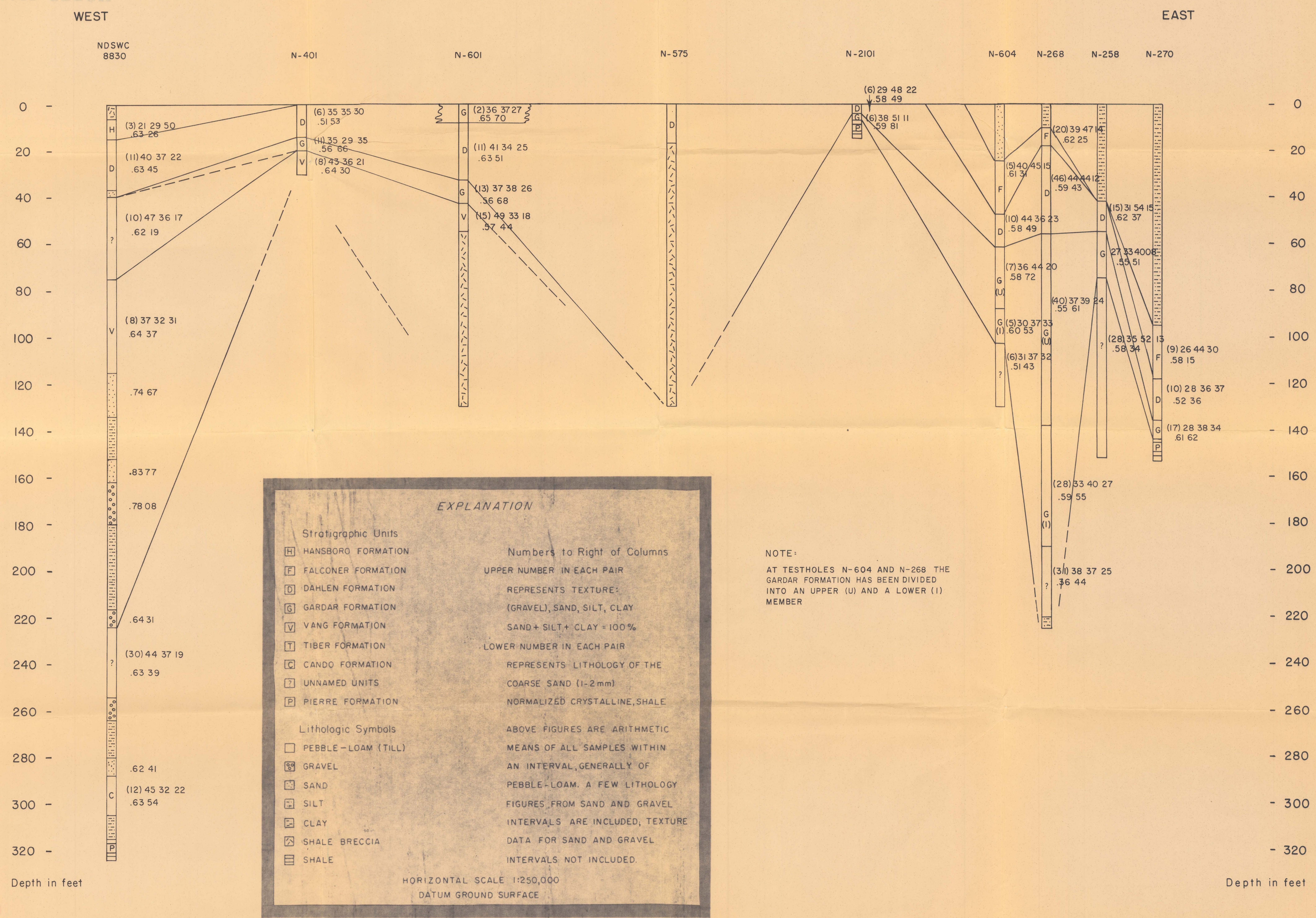
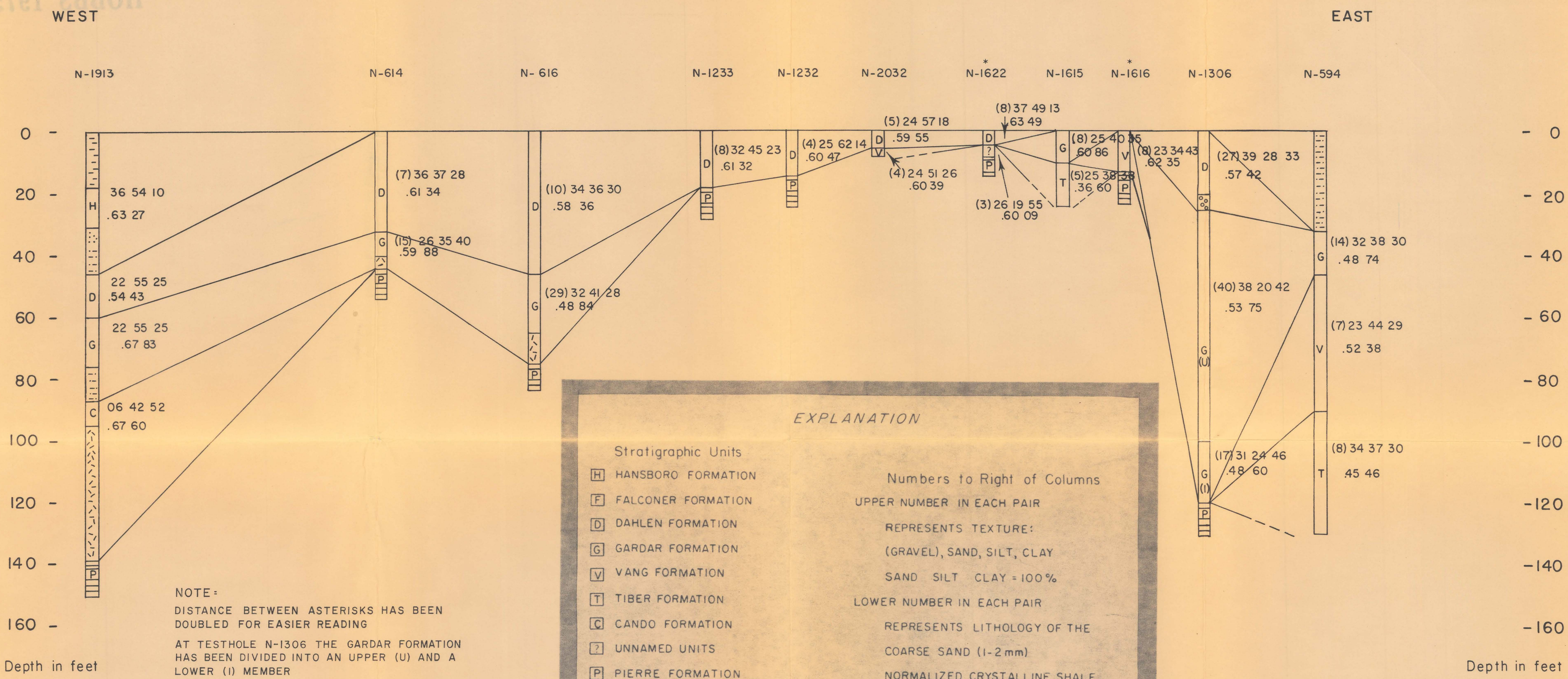


PLATE 6 STRATIGRAPHIC CROSS SECTION FROM CANDO TO EDINBURG



NOTE:

DISTANCE BETWEEN ASTERISKS HAS BEEN DOUBLED FOR EASIER READING

AT TESTHOLE N-1306 THE GARDAR FORMATION HAS BEEN DIVIDED INTO AN UPPER (U) AND A LOWER (l) MEMBER

EXPLANATION

Stratigraphic Units

- H HANSBORO FORMATION
- F FALCONER FORMATION
- D DAHLEN FORMATION
- G GARDAR FORMATION
- V VANG FORMATION
- T TIBER FORMATION
- C CANDO FORMATION
- ? UNNAMED UNITS
- P PIERRE FORMATION

Lithologic Symbols

- PEBBLE-LOAM (TILL)
- GRAVEL
- SAND
- SILT
- CLAY
- SHALE BRECCIA
- SHALE

Numbers to Right of Columns

UPPER NUMBER IN EACH PAIR REPRESENTS TEXTURE: (GRAVEL), SAND, SILT, CLAY SAND SILT CLAY = 100%

LOWER NUMBER IN EACH PAIR REPRESENTS LITHOLOGY OF THE COARSE SAND (1-2 mm) NORMALIZED CRYSTALLINE, SHALE

ABOVE FIGURES ARE ARITHMETIC MEANS OF ALL SAMPLES WITHIN AN INTERVAL, GENERALLY OF PEBBLE-LOAM. A FEW LITHOLOGY FIGURES FROM SAND AND GRAVEL INTERVALS ARE INCLUDED, TEXTURE DATA FOR SAND AND GRAVEL INTERVALS NOT INCLUDED.

HORIZONTAL SCALE 1:250,000

DATUM GROUND SURFACE

PLATE 7 STRATIGRAPHIC CROSS SECTION FROM ROLLA TO INKSTER

PLATE 8 THICKNESS AND LITHOLOGY OF THE HANSBORO AND FALCONER FORMATIONS

PLATE 9 THICKNESS AND LITHOLOGY OF THE DAHLEN FORMATION

PLATE 10 THICKNESS AND LITHOLOGY OF THE GARDAR FORMATION

PLATE II THICKNESS AND LITHOLOGY OF THE VANG FORMATION

PLATE 12 THICKNESS AND LITHOLOGY OF THE TIBER FORMATION

PLATE 13 THICKNESS AND LITHOLOGY OF THE CANDO FORMATION

PLATE 14 THICKNESS AND LITHOLOGY OF VARIOUS UNCORRELATED UNITS

PLATE 15 THICKNESS AND SURFACE MORPHOLOGY OF THE DAHLEN FORMATION IN AN AREA FROM LANGDON TO THE INTERNATIONAL BOUNDARY